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Author(s):	Svyatsky, Daniil
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INSTITUTIONAL COMPUTING REPORT

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Title: Radiation Belt Remediation: A Complex Engineered System (RBR-ACES)

PI: Daniil Svyatsky (T-5, e-mail: dasvyat@lanl.gov, phone: 606-2124)

Co-Investigators: Gian Luca Delzanno (T-5, e-mail: delzanno@lanl.gov, phone: 7-2604), Pedro Resendiz (T-5, e-mail: resendiz@lanl.gov, phone: 665-8340), Kevin Shipman (AOT-AE, phone: 667-0387), Gregory Scott Cunningham (ISR-1, email: cunning@lanl.gov phone: 667-2562)

We have performed the simulation campaigns in support of LDRD-DR project Radiation Belt Remediation: A Complex Engineered System (RBR-ACES). This project involves modeling wave generation and wave propagation in plasma environment and studying the effect of waves on the distribution of high energy electrons with the focus on electrons appeared after a high-altitude nuclear explosion (HANE). One of the major goal of this research is strong validation of the numerical models with laboratory experiments and space-based experiments and observations.

Simulation campaigns were performed with three codes. The first is a Particle-In-Cell (PIC) code called CPIC. The code is formulated in curvilinear geometry and couples the standard PIC algorithm with algorithms for the generation and adaptation of the underlying computational mesh. It conforms to complex objects like a spacecraft and can place more grid points in regions where higher resolution is needed. The code also features a scalable solver based on the multigrid algorithm and is fully parallelized via domain decomposition and MPI. The second code is the SpectralPlasmaSolver (SPS). SPS solves the Vlasov-Maxwell equations with an Hermite decomposition of the plasma phase-space density together with a discontinuous-Galerkin discretization in space. Because of its PETSc interface, SPS can use both explicit and implicit time integrators and it features nearly optimal scaling up to 30,000 cores. The third code is the 3D Dynamic Radiation Environment Assimilation Model (DREAM3D). DREAM3D was developed to provide accurate, global specification of the Earth's radiation belts and to better understand the physical processes that control radiation belt structure and dynamics. DREAM3D is designed using a modular software approach in order to provide a computational framework that makes it easy to change components such as the global magnetic field model, radiation belt dynamics model, boundary conditions.

Our main results are:

1. We have performed first-principle-based simulations of artificial wave injection with dipole antenna using CPIC capabilities. One of the major focus of this research is validation of simulation results versus available data from ARFL DSX mission. CPIC has been used to model a small dipole antenna with parameters representing the DSX experiment and simulation results show good agreement with experimental data. The results of high resolution simulations have been compared with the linear theory predictions. Based on these comparisons we can conclude that it is important to include nonlinear effects into consideration especially for high voltage regimes. Artificial wave injection leads to the sheath formation around an antenna. Simulation results demonstrate reasonably good agreement with Song's sheath model [J. Geo. Res. 112, A03205 (2007).
2. We continued studying the effect of the dynamics of the pulse on artificial wave generation. Pulses evolve due the initial energy spread originating in the accelerator and under the action of the space-charge electric field and the Lorentz force. As they spread longitudinally and reach a size comparable to the wavelength of the modes that are excited, radiation is quenched. A relatively simple model of pulse dynamics was included in SPS and simulations were performed to understand its impact on the wave generation process. To simulate more realistic wave generation we rely on inclusion of macroparticle representation of beam files. A new methodology has been developed within SPS framework to enable SPS simulations using numerical beam description.

3. Another research direction is the predicting of the effect of the waves on evolution of high energy (MeV) electrons. Using DREAM3D code we simulated evolution of HANE electron distribution in the presence of waves and predicted impact on satellites. The significant amount of simulations was performed to validate DREAM3D predictions against available data (PROBA-V instrument electron scattering data, Van Allen Probe (VAP) data). Several improvements to DREAM3D code lead to successful modelling of dynamics of injected MeV electrons and reproduction of observational decay times.

List of presentations and publications:

Results from this work have been presented at several conferences:

Presentations:

1) American Geophysical Union Fall Meeting December 2021. (New Orleans, Louisiana, United States). Six presentations.
2) American Physical Society Conference, November 2021. (Pittsburgh, Pennsylvania, United States). Two presentations.
3) International Conference on Electromagnetics in Advanced Applications (Honolulu, Hawaii, United States). Three presentations
4) AAPPS-DPP2021, September 2021, (Japan). One presentation

The following articles have resulted from the simulation campaigns

1. P. Colestock, G. L. Delzanno, Q. R. Marksteiner, K. A. Shipman, N. Yampolsky (2021), A Comparison of Wave Emitters for Applications in the Inner Magnetosphere Prepared for: IEEE Transactions on Plasma Science LA-UR-21-20126

2. Ghaffari, R., C. Cully, D. L. Turner, G. D. Reeves, and C. A. Kletzing (2020), Characteristics of Electron Precipitation during 40 Substorm Injections Inferred via Subionospheric VLF Signal Propagation Journal of Geophysical Research: Space Physics, 125 (11) e2019JA027233 doi:10.1029/2019JA027233. LA-UR-20-24385

3. Nonlinear coupling of whistler waves to oblique electrostatic turbulence enabled by cold plasma Roytershteyn, V. ; Delzanno, Gian Luca Physics of Plasmas 28, 042903 (2021) LA-UR-20-20992

Funding

This IC project directly supports an ongoing DR to develop a radiation belt remediation strategy to protect the country from the consequences of HANE. The simulations also support a rocket experiment funded by NASA, called Beam-PIE, and expected to launch in March 2023. A LDRD-ER pre-proposal to perform Beam-PIE data analysis and modeling comparisons has currently advanced to the full proposal submission and is being prepared. By further exercising our numerical tools in new regimes, this project also supports indirectly new research directions in plasma-material interaction. These include the 1) monitoring and tracking of small (less than 10 cm characteristic size) orbital debris in space, for which a white paper has been submitted in response to a I-ARPA request for information, 2) the removal of large (bigger than 10 cm) orbital debris in space, for which a DR pre-proposal has been submitted (not selected for full proposal) and 3) understanding signatures of hypersonic objects traveling through the ionosphere/atmosphere.